Extraneous Interference on Submarine Telegraph Cables

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SYNOPSIS: In order to avoid a considerable reduction in speed of operation, which would have resulted on account of the unusually large parasitic disturbances encountered in the neighborhood of New York, the New York-Azores permalloy loaded cable was equipped with a new type of earth connection consisting of a conductor extending 100 nautical miles to sea and there connected to earth through an artificial line.

This paper presents the theory of the new type of sea earthing arrangement and discusses the sources of extraneous interference and the manner in which it is picked up by submarine cables. A method is developed for estimating the magnitude of terminal extraneous interference in the case of any particular cable.

AMONG the factors limiting the speed of operation of long submarine telegraph cables one of the most important is the mutilation of the received signals by electrical disturbances picked up along the cable and transmitted with the incoming signal to the receiving instrument. The nature of this disturbance is shown in Fig. 1 which is an oscillographic record over a short period of time of the difference of potential across the terminals of the receiving instrument of a cable system, at a time when no signals were being received over the cable. Although the complete signal correction networks were not in circuit at the time this record was taken, the latter is representative of the form of the extraneous disturbance that would be superposed on the record of an incoming signal. It is evident that unless the signal amplitude is sufficiently large compared with the amplitude of interference, the latter will seriously interfere with the interpretation of the siphon recorder tape or with the functioning of relays operated by the signal current. That this condition constitutes a limit on the speed of operation of the cable is indicated by Fig. 2 which shows the amplitude of a signal, received over a typical transatlantic cable, as a function of

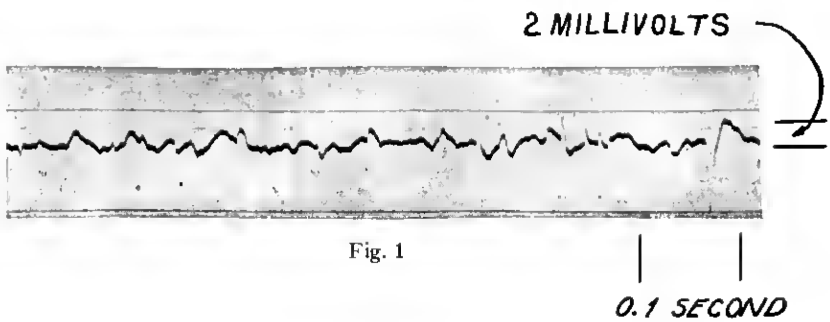
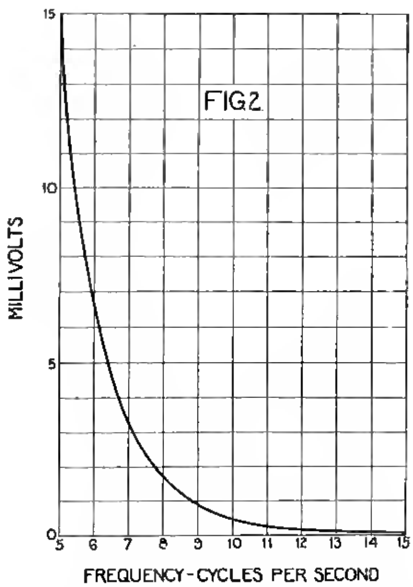


Fig. 1

the signal frequency.[1] It is evident, that corresponding to the minimum amplitude at which signals are just legible through interference, there is, for a given value of sending voltage, a maximum speed of signalling which cannot be exceeded, without danger of serious mutilation of the signal. If by any means the magnitude of the extraneous interference can be diminished, signals of smaller amplitude can be employed and the speed of operation consequently increased.



The present paper will be devoted to a description of the manner in which extraneous interference is picked up by submarine cables, with a discussion of the influence of various factors such as depth of water, cable structure and operating conditions. There will also be described a method of reducing interference by a modification of the cable structure. This method has been remarkably successful in the case of the New York-Azores continuously loaded cable,[2] and has helped to make available the great gain in operating speed due to continuous loading, which is the outstanding feature of this cable installation.

The disturbances encountered on submarine cables are due mainly to induction from extraneous electromagnetic fields in the sea water,

[1] The signal frequency is defined as the fundamental frequency involved in a succession of alternately positive and negative unit impulses.

[2] Buckley, O. E., *Journal A. I. E. E.*, Vol. XLIV, p. 821, August 1925, *Bell System Technical Journal*, Vol. IV, No. 3, July 1925.

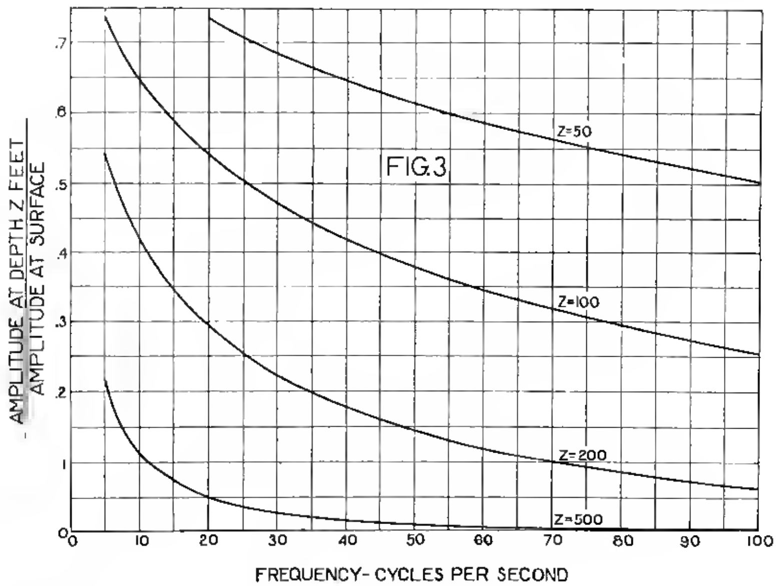
arising from a variety of sources, which may be broadly grouped into two classes. The first class comprises artificial sources, such as electrical power or railway systems in the neighborhood of the cable terminals. Currents circulating between the various earth connections of such systems give rise to electromagnetic fields in the earth and sea water, which fields may have the form of transient surges or pulses, or may be periodic in nature. The second class includes the various manifestations in the atmosphere or at the surface of the earth, such as electric or magnetic storms, which are also responsible for the disturbances in radio communication known as "static." Very little definite data is available regarding the magnitude and character of the natural disturbances affecting submarine cables, but it is found that, as in the case of static, the intensity of such effects is influenced by a number of factors, the season of the year and the geographical location being among the most important. At times of unusual activity, such as that accompanying the aurora polaris or local electrical storms, the voltages induced in the cable conductor are so large as to prohibit operation of the cable.

Except in the case where the source is in the immediate vicinity of the cable, the effect of any disturbance upon the cable can be considered as the result of a fluctuation of potential at the surface of a massive conducting medium, the ocean, which gives rise to electromagnetic waves which are propagated in all directions from the source and which penetrate the interior of the conducting medium according to the well-known laws governing "skin effect." Due to the presence of varying electric and magnetic fields in the sea water adjacent to the cable, an electromotive force is induced in each section of the cable conductor, and the resulting current is transmitted along the conductor to the cable terminal, combining with the currents due to electromotive forces induced in other sections to make up the total extraneous interference.

At the surface of the ocean the disturbance may take a variety of forms, for instance a succession of pulses or a train of damped oscillations. In any case the most convenient method of following the disturbance through the sea water into the cable conductor and along the conductor to the cable terminal is to consider the disturbance made up of a number of sinusoidal components of all frequencies from zero to infinity, the relative amplitudes and phases of the various components being determinable from the wave shape of the disturbance by the methods of Fourier analysis. The transmission characteristics of the interference transmission system at any particular frequency can then easily be studied, and finally the total effect of the original dis-

turbance can be obtained by summation of disturbances of all frequencies.

The extent to which electrical disturbances penetrate below the surface of the ocean can be determined from the theory of induction of currents in continuous media, where it is shown that the components of the electric (E) and magnetic fields (H) parallel to and at a distance



z below the surface of an infinite plane conductor are given by the formulas:[3]

$$E = E_o\, \epsilon^{-kz},\ H = H_o\, \epsilon^{-kz},\ k = 2\pi\sqrt{2\lambda i f}, \tag{1}$$

where E_o and H_o are the values of E and H at the surface, λ is the electrical conductivity of the medium and f is the frequency. Employing the value of λ for sea water and expressing z in feet, gives

$$k = 1.35 \times 10^{-3}\sqrt{f}\ (1+i).$$

The curves of Fig. 3, computed from formula (1), indicate the manner in which sinusoidal disturbances of frequencies in the telegraph range are attenuated by various depths of sea water. It can be seen that the magnitude of a disturbance falls off rapidly as it penetrates the water; also that this attenuating effect is greater the higher the frequency. At a depth of one or two miles, at which the greater part

[3] Jeans "Electricity and Magnetism," 2nd Edition, p. 477.

of the typical transoceanic cable is submerged, only the extremely low frequency components of the surface disturbance are encountered to an appreciable degree. In the vicinity of the terminals, however, where the water is comparatively shallow, the cable is exposed to the higher frequency components of the disturbances, and it is usually in these sections that the greater part of the most troublesome disturbances is picked up. This is especially true in localities where the zone of shallow water extends a considerable distance from shore. Such a case is shown in Fig. 4, which represents a typical profile of the ocean bottom for the shallow water portion of a cable terminating at New York.

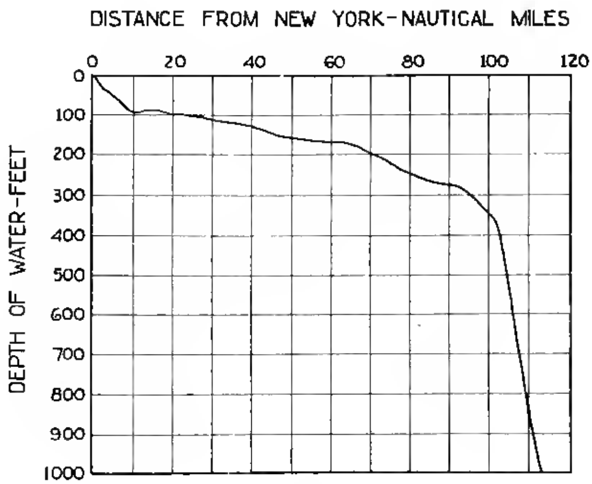


FIG. 4

The phenomena attending the induction of an electromotive force in the cable conductor by an electromagnetic field are rather complicated and difficult of exact computation. In the first place, on account of the change in electrical constants in passing from sea water to ocean bottom, the electric and magnetic field intensities in the neighborhood of the cable are somewhat different than indicated by equation (1). The influence of this factor upon the final result is in general small compared with that of the other factors that we are considering, and, on account of our lack of knowledge concerning the electrical characteristics of the ocean bottom, theoretical discussion would be of little practical value. A second factor is the shielding effect of the armor wires and metallic tapes surrounding the core. No attempt will be made in the present paper to work out an analytical solution of this

problem. There is available, however, from a recent study of the problem of the sea return resistance of a submarine cable,[4] information that enables us to compare the behavior of various cable structures from the point of view of shielding. One of the results of this work was the determination of the degree to which the shielding effect of the metallic sheath around the cable causes the returning signal current to flow in this sheath rather than in the surrounding sea water. It is obvious that the greater the tendency of the metallic sheath to confine the return current to itself, the more effective the sheath will be in reducing the pick-up of interference. Allowing for the two effects just discussed, it is evident that the electromotive force induced in unit length of the cable conductor is given by an expression of the form

$$e = A\ E_o\, \epsilon^{-kz} \tag{2}$$

where A is a multiplier, the value of which will be determined only on a relative scale.

The electromotive force induced in any section of the cable conductor gives rise to sinusoidal currents and potentials which are transmitted in both directions along the conductor in accordance with well-known laws. For simplicity we will assume that the cable is terminated at both ends in its characteristic impedance, Z, the result corresponding to any other values of terminal impedances being readily determinable if needed.[5] Then an electromotive force $e\,dx$, induced in a short section of cable of length dx, distant x from the terminal, will result in a current

$$\frac{e\,dx}{2Z}\,\epsilon^{-\gamma x} \tag{3}$$

at the terminal. If the electromotive force per unit length e is picked up uniformly over a length of cable extending from $x=a$ to $x=s$, then since the impedance in each direction from the point is Z, the resulting current at $x=o$ will be

$$\frac{e}{2Z}\int_a^{a+s} dx\,\epsilon^{-\gamma x} \tag{4}$$

$$= \frac{e}{2Z}\,\epsilon^{-a\gamma}\,\frac{1-\epsilon^{-s\gamma}}{\gamma}$$

[4] Carson and Gilbert "Transmission Characteristics of a Submarine Cable," *Jour. Franklin Inst.*, Vol. 192, p. 705, 1921, and *Electrician*, Vol. 88, p. 499, 1922; *Bell System Technical Journal*, Vol. I, No. 1, July 1922.

[5] Heaviside, "Electromagnetic Theory," Vol. 2, p. 75.

Thus the effect at $x=o$ is the same as if an electromotive force $e\frac{1-\epsilon^{-s\gamma}}{\gamma}$ had been impressed at $x=a$.[6]

It would now be possible to assume a definite form of disturbance at the surface of the ocean, and by applying the principles that have been discussed in the preceding pages, to work out for any particular cable the wave shape of the resulting interference at the cable terminals. On account of our lack of knowledge as to what might be considered a typical disturbance at the surface of the ocean, such results would be merely speculative, and would be of no practical value in predicting the actual terminal interference that might be expected. A much better scheme is to compute for each cable, what may be called the interference susceptibility, this being defined, for a particular frequency, as the integral

$$\int A \cdot \epsilon^{-kz} \cdot \epsilon^{-\gamma x} \cdot dx. \tag{5}$$

the integration extending over the entire cable. A is a factor which takes account of the shielding by armor wires, and changes at each point on the cable where the armoring changes. z is the depth of immersion at a distance x from the terminal, the relation between z and x being obtainable from the profile curve of the cable route. By comparing the susceptibility-frequency curves for two cables we can obtain an idea of the relative disturbances to be expected on the cables, with the possible exception of that part arising from sources in close proximity to the cables. For the latter type of interference special considerations are necessary.

In drawing conclusions from a susceptibility-frequency curve it is essential to bear in mind that, although the disturbance at the cable terminal is a composite of sinusoidal voltages and currents of all frequencies from zero to infinity, we are principally concerned with the

[6] An interesting conclusion to be drawn from equation (4) is that the contributions from various portions of a long section of cable due to a uniform disturbance tend to neutralize each other, on account of the fact that they arrive at $x=a$ in various phases. Since γ is equal to $\alpha+j\beta$, where α is the attenuation constant and β the phase constant, both per unit length, the quantity $\epsilon^{-s\gamma}$ can be represented graphically by a vector of length $\epsilon^{-s\alpha}$ and angle $(-s\beta)$. If α were zero the value of the factor $1-\epsilon^{-s\gamma}$ would be zero for $s\beta=o$, 2π, 4π, 6π, etc. That is the disturbance picked up over a length of cable $s=\frac{2n}{\beta}$, n being any integer, would have no effect at the terminal of the cable. On account of the fact that a is not zero, the quantity $\epsilon^{-s\gamma}$ is less than unity for all the above values of s except $s=o$, and complete neutralization of the disturbance does not occur. In the case of an inductively loaded cable, however, for a given value of α, β is many times greater than the value for the corresponding non-loaded cable. This means that neutralization of interference picked up on the loaded cable is much more complete than in the case of a non-loaded cable.

components lying within a certain frequency range, the limits of which depend upon the speed of signalling. This is due to the fact that the characteristics of an ordinary submarine cable are such that the low frequency components of a signal are transmitted with much less di-diminution of amplitude than are the higher frequency components. Consequently [7] it is found necessary, in order to render the signal intelligible, to employ a correcting network at the receiving terminal, one function of which is to attenuate the arriving low frequency components so that they finally are in the proper proportion to the higher frequency components. Also it is found that frequencies which are higher than about one and one-half times the signal frequency are not required in order to obtain intelligible signals, so that the receiving network can be designed to remove disturbances of the higher frequencies. The receiving apparatus therefore acts as a band filter towards the interference arriving at the terminal and emphasizes the part played by the components of interference of frequencies in the neighborhood of the signal frequency. On this account it is possible, in the majority of cases, to obtain the significant portion of the susceptibility-frequency curve by limiting the integration in (5) to the portion of the cable submerged to a depth of approximately 1000 feet or less, since, as has been previously indicated, only disturbances of extremely low frequencies are picked up on the deep water portion of the cable.

Given the problem of predetermining the interference at the terminal of a projected cable, the following procedure can be employed:

1. Over a period of time sufficiently long, a series of records of interference is taken on a cable terminating in the same general neighborhood as the proposed cable. Oscillographic records of the type shown in Fig. 1 are very desirable for this purpose.

2. From these records, and from the computed susceptibility-frequency curves of the existing and projected cables the interference on the latter can be predicted.

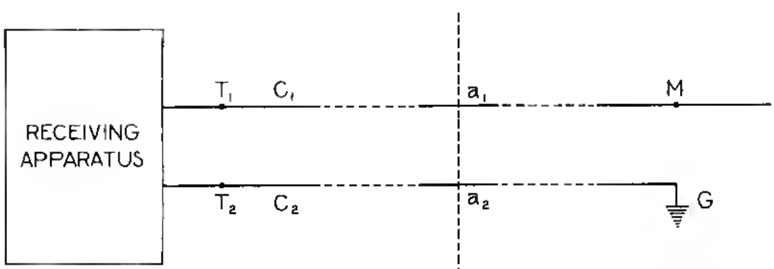
The method just described was applied to predetermine the interference at the terminals of the New York-Azores permalloy loaded cable. At the Azores terminal the cable reaches deep water within a few miles of the terminal, and the results indicated that the magnitude of interference to be expected would be sufficiently small to permit of signalling at the speed at which it was desired to operate. At the New York terminal, however, the ocean for a distance of about 100 nautical miles is comparatively shallow, and cables in this vicinity are exposed to rather severe disturbances. This is partly due to unusually strong

[7] See Milnor "Submarine Cable Telegraphy," Trans. *A. I. E. E.*, Vol. 41, p. 20, 1922.

stray fields from the numerous electric railway systems in the neighborhood of New York. By means of an amplifier and a recording string oscillograph records were obtained of the interference on the Western Union Telegraph Company's non-loaded cables terminating at New York. In taking these records a number of terminal networks were employed, with various attenuation characteristics, in order to obtain an idea of the distribution of interference with respect to frequency. Another series of tests was made, on board the Western Union cableship "Clowry," during which a cable was raised from deep water, cut, and interference studies made on the two parts of the cable. A study of these results according to the method that has just been described indicated that unless some means were employed for reducing the terminal interference, a great sacrifice of signal speed would have to be made, at least on westbound traffic. The remedy that was adopted is a special type of earth connection 100 miles at sea, to which the ground terminal of the receiving apparatus is connected. The theory of this arrangement will now be developed.

For the purpose of diminishing extraneous interference there is provided on most submarine cables an earthing arrangement, which, as shown diagrammatically in Fig. 5, consists of a core C_2 of the same general type as that used in the main cable C_1, and which may be

FIG 5



armored either with the main cable or in an independent sheath. This core usually extends for a distance of a few miles from the shore, to a point G, where the conductor of the core is grounded on the armor of the main cable. The receiving apparatus associated with the main cable conductor is then connected to earth through the sea earth conductor and the earth connection at its sea terminal. It is evident that if the main core and the sea earth core are close together they will both be exposed to the disturbances encountered between the terminal and the point where the sea earth conductor is grounded. If the two cores

reacted in the same degree to these disturbances, then it is clear that corresponding to each disturbing impulse at T_1 due to pick-up at any point a_1 on T_1M there would be an equal impulse at T_2 due to pick-up at a_2 the corresponding point on $T_2\,G$ and there would be no resulting difference of potential impressed on the receiving network due to these disturbances. As a matter of fact the section $T_2\,G$ does not react to disturbances in the same manner as the section $T_1\,M$, even though the two cores have identical linear characteristics. Although the impedances looking landward from a_1 and a_2 will be equal, the impedances looking seaward from the two points are likely to be widely different, and the impedances into which electromotive forces induced at a_1 and a_2 work will not be equal. The same disturbance will therefore set up currents of different amplitudes in the two conductors, and there will be a difference of potential between T_1 and T_2 which will be indicated on the receiving instrument. Another way of looking at this effect is to consider the disturbances picked up at a_1 and a_2 as resulting in transient waves of potential and current which are propagated along the two conductors in both directions from the points of pick-up. The waves travelling from a_1 to T_1 are equal to the corresponding waves travelling from a_2 to T_2. A similar equality holds for the waves travelling from a_2 to G and from a_1 to M. On arriving at G the waves on the sea earth conductor are reflected and travel back along the conductor, finally arriving at T_2. Since there is no corresponding reflection on the main conductor, there will be an unbalanced disturbance, the magnitude of which depends upon the amount by which the disturbance was attenuated in travelling over the route a_2-G-T_2.

The remedy [8] for the condition just described is to eliminate reflection at the sea end of the sea earth conductor, or, if for any reason, there is a reflection at the point M, to balance it with an equal reflection at the point G. This can be done by grounding the sea earth conductor at G through a network having an impedance that bears the same relation to the impedance of the conductor $G\,T_2$ as the impedance of the cable seaward of M bears to the impedance of the conductor $M\,T_1$. When the two cores $T_1\,M$ and $T_2\,G$ are alike, the impedance of the network should equal the impedance of the main cable at M.[9]

[8] Osborne, U. S. Patent 1,390,580—1921.
Heurtley, Br. Patent 198,978—1923.
Gilbert, Br. Patent, 218,261—1926.

[9] There is one important type of disturbance which has not been dealt with in the preceding discussion, namely, that due to the signal currents on cables which cross or lie close to the cable in which we are interested. It is evident that the electromotive forces induced in the cable conductor due to such causes behave in the same manner as any other disturbing electromotive force and that the magnitude of their effect can be reduced by the use of a balanced sea earth conductor terminated at a point beyond the region of disturbance.

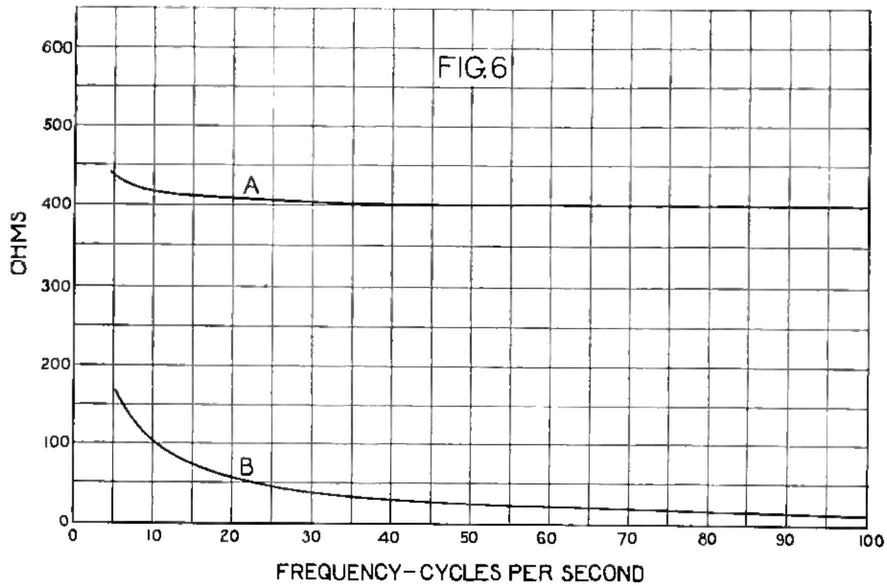
With this source of unbalance between the main core and the sea earth core removed or greatly reduced, it becomes increasingly important that the factors affecting the pick-up and the transmission of interference on the two cores be made as nearly as possible the same. In manufacturing the cable, core lengths should be paired off in such a manner that the electrical constants of any portion of the sea earth core match the constants of the corresponding portion of the main core, and the two cores should preferably be armored together.

By an extension of the method employed in deriving formula (5) an expression for the interference-susceptibility frequency characteristic of a cable having a balanced type of sea earth can be derived. This expression will consist of two terms, the first representing the resultant interference due to lack of balance between the sea earth conductor and the main core, and a second term, similar in form to (5), representing the interference picked up on the portion of the cable beyond the sea earth termination. Because of the difficulties involved in balancing, there is a value below which the first term cannot practically be reduced, which residue amounts to a few per cent of the magnitude of interference that would be encountered on this portion of the cable if the balanced type of sea earth were not employed. The second term can be reduced to any desired value by terminating the sea earth in water of sufficient depth. It is evident that when the sea earth has been extended to a point where the second term is small compared with the first, the limit of interference reduction is reached.

The question as to how far from shore the sea earth should be located in a particular case is an economic problem, the optimum location being that where the increase in value of the cable, due to diminution of interference by further extension of the sea earth, balances the additional cost of making the extension. In some cases it is found economical to obtain the desired ratio of signal-to-interference by means of a more efficient and expensive core rather than by an extended sea earth conductor. In the case of transatlantic cables terminated at points on the English Channel, or on the North Sea, for example, sea earth conductors several hundred miles in length are required in order to get a deep water termination. By increasing the weight of the main conductor, thereby increasing the amplitude of signals received over the cable, a greater amount of interference can be tolerated, in which case a comparatively short sea earth can be employed, just long enough to get rid of local interference and of the pick-up of signals from cables terminating nearby.

An inductively loaded submarine telegraph cable possesses characteristics which make the balanced type of sea earth particularly

adaptable. Fig. 6 shows the real and imaginary parts of the characteristic impedance of a typical cable designed to operate at a speed corresponding to about 60 c.p.s. It is evident that for all frequencies above 20 c.p.s. the impedance can be approximated very closely by a pure resistance of about 400 ohms. In contrast to this, the character-



A. Resistance Component. *B*. Reactance Component (negative)

istic impedance of a non-loaded type of cable varies with frequency and has a reactance component about as large as the resistance component. In the case of the loaded cable the problem of designing a terminating network for the sea earth conductor is therefore comparatively simple, being a matter of finding a method of including in the cable structure a resistance of several hundred ohms. It is true that a network of this sort does not provide a good balance for frequencies much below 20 c.p.s., and components of interference of these low frequencies will be found at the cable terminals due to the lack of balance between the main cable and the sea earth. As was previously pointed out, however, these components will be so greatly attenuated by the signal correcting networks that their effect upon the receiving instrument will be inappreciable. This is illustrative of a general property of the loaded telegraph cable, namely, that when a cable is suitably designed for the frequency at which it is to be operated its characteristic impedance approximates closely to a resistance over a

range of frequencies which extends considerably below the signal frequency, so that the resultant interference due to employing a resistance termination for the sea earth conductor will be attenuated to such a degree by the signal correction networks that it will in general have a negligible effect upon the receiving instrument. Moreover, it is probable that a considerable amount of low frequency disturbance is picked up beyond the sea earth and the gain obtained by improving the balance for these frequencies would not be very great.

A practical design for the terminating resistance consists of a length of several hundred feet of stranded wire, approximately 0.05 inch in diameter, of high resistivity material, insulated with gutta percha. After being joined at one end to the sea end of the sea earth core, the insulated conductor is served with jute and laid up with the main core for armoring exactly in the same manner as any other portion of the sea earth core. The free end of the conductor is grounded by connecting to the armor wires in the usual manner. A structure of this sort satisfies very completely the requirement of simplicity and lightness, and is as easily maintained as a length of ordinary cable similarly located.

There is a second characteristic of the loaded type of cable that tends to simplify the problem of the design of a balanced type of sea earth. It has been shown that the portion of the extraneous interference that it is most desirable to eliminate consists of the components of

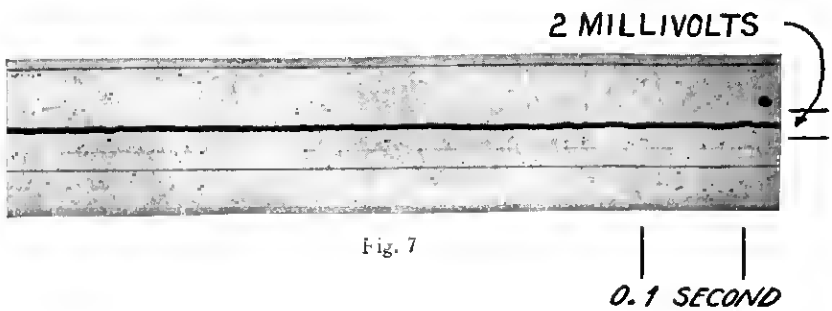


Fig. 7

frequencies in the neighborhood of the signal frequency. Since the operating speed of a loaded cable is five to ten times that of the corresponding non-loaded cable, it is evident from the preceding discussion that in order to effect a given reduction of interference in any particular locality, the sea earth of the loaded cable can be located closer to shore and in shallower water than in the case of the non-loaded cable.

In the case of the New York-Azores cable the balanced type of sea earth has been very effective in reducing extraneous interference. Fig. 7 is an oscillographic record of the terminal interference between

this cable and its sea earth taken at the same time and under the same conditions as Fig. 1, which is the record of terminal interference on an adjacent non-loaded cable provided with the ordinary type of sea earth. In both cases a large condenser was inserted between the cable and the amplifier to reduce the "zero wander" due to components of very low frequency. Comparison of the two records indicates that the interference on the cable with the ordinary sea earth is about ten times that on the cable with the balanced sea earth. The contrast between the two types of sea earth is still more pronounced at times when terminal interference is unusually large. It has been found possible, for example, to operate the New York-Azores cable during violent local electrical storms when neighboring cables were compelled to cease operation.